# *HYDRODYNAMIC STUDY OF THREE PHASE SEMI FLUIDIZED BED WITH IRREGULAR AND HOMOGENEOUS BINARY MIXTURES*

*A Project submitted to the*
*National Institute of Technology, Rourkela*

*In partial fulfilment of the requirements*
*for*
**Bachelor of Technology (Chemical Engineering)**

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# CERTIFICATE

This is to certify that the thesis entitled **Hydrodynamic study of Three Phase semi Fluidized Bed with Irregular and homogeneous binary mixtures,** submitted by **Bhabani Sankar Das & Biswajeet Patnaik** to National Institute of Technology, Rourkela is a record of bonafide project work under my supervision and is worthy of the partial fulfillment for the degree of Bachelor of Technology (Chemical Engineering) of the Institute. The candidates have fulfilled all prescribed requirements and the thesis, which is based on candidates' own work, has not been submitted elsewhere.

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# ABSTRACT

Fluidization refers to a process by which a fluid like state is imparted to granular solid particles by the passing of a fluid upwards through the bed of particles. A semi fluidized bed is characterized by a fluidized bed and a packed bed in a series within a single contacting vessel. Gas-liquid-solid semi fluidization is defined as an operation in which a bed of solid particles is suspended in gas and/or liquid upward flowing media due to the net gravitational force on the particles and the motion of the particles is restricted by a top restraint. Such an operation generates intimate contact between the gas, liquid and solid particles in these systems and provides substantial advantages for applications in physical, Chemical and biochemical processing involving gas, liquid and solid phases.

The experiments were conducted using liquid as the continuous phase and gas as the discontinuous phase. In this work air, water and dolomite (2.31mm, and 1.7mm) are used as the gas, liquid and solid phases respectively. The experiments were carried out in a 100 mm ID of 2m height vertical Plexiglas column.

Knowledge of minimum liquid semi fluidization velocity is essential for the successful operation of gas-liquid-solid semi fluidized beds. Bed pressure measurements have been made to predict the values of the minimum liquid semi fluidization velocity. In the present work, hydrodynamic characteristics viz., the pressure drop, bed expansion of a co-current gas-liquid-solid semi fluidized bed has been studied. These have done in order to develop a good understanding of each of the flow regime in gas-liquid and liquid-solid semi fluidization.

The effect of static bed height, particle size, liquid velocity and gas velocity on hydrodynamics parameters like minimum semi fluidization velocity, pressure drop, expansion ratio have been investigated. Experimental study based on statistical design has been made to investigate the expansion ratio of semi fluidized bed.. The experimental values have been compared with those predicted by the correlations and have been found to agree well.



**Keywords:** Semi fluidization, packed bed formation, minimum and maximum semi fluidization velocity, expansion ratio, factorial design.

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# NOMENCLATURE:

| | |
|---|---|
| $d_p$ | Particle diameter, m |
| $H_{pa}$ | Top packed bed height, m |
| $H_s$ | Static bed height, m |
| $U_l$ | Superficial liquid velocity, m/s |
| $U_g$ | Superficial gas velocity, m/s |
| $U_{lmsf}$ | Minimum liquid semi fluidization velocity, m/s |
| $U_{gmsf}$ | Minimum gas semi fluidization velocity, m/s |
| $U_{lMsf}$ | Maximum liquid semi fluidization velocity, m/s |
| $U_{gMsf}$ | Maximum gas semi fluidization velocity, m/s |
| R | Expansion ratio |
| $V_g$ | Gas flow rate (lpm) |
| $V_l$ | Liquid flow rate (lpm) |

# CHAPTER 1

# INTRODUCTION

A semi fluidized bed is characterized by a fluidized bed and a packed bed in a series within a single contacting vessel. The phenomenon of semi fluidization was first reported which was related to mass to mass transfer in a liquid solid system. A semi fluidized bed is formed when a mass of fluidized particles is compressed by fluids with a porous retaining grid at the top. Fixed bed or packed bed, batch and continuous fluidization and semi fluidization all are two phase phenomena. In case of batch fluidization if the free expansion of the bed is restricted by the introduction of porous disc or sieve and the fluid velocity is increased the particles are fluidized and the expansion starts with further increase in velocity of fluid the particles will be carried and formation of a fluid bed results at the top. So by the introduction of restraint some of the particles are distributed to the bottom section which is in the form of a packed bed. This is known as semi fluidization which can be considered as a new type of solid fluid contacting method which combines features of both fixed and fluidized beds. Semi fluidization is a compromise between the two and the particles can be distributed into the two sections as desired by choosing the parameters like position of restraint, fluid velocity etc.

The literature available so far on semi fluidization can be classified under the following heads

i) Studies oriented towards prediction of the onset and maximum semi fluidization velocities.
ii) Studies oriented towards the prediction of packed bed height.
iii) Studies on total pressure drop.
iv) Studies on mass transfer, reaction kinetics and other related fields.

# CHAPTER 2

# LITERATURE REVIEW

Semi fluidization is a new and unique type of fluid-solid contacting technique which has been reported recently. This type of technique overcomes the disadvantages of fluidized bed namely back mixing of solids, attrition of solids and problems involving erosion of surfaces. This also overcomes certain drawbacks of packed bed, viz. non-uniformity in temperature in the bed, channel flow and segregation of solids. An extensive review relating to various aspects of hydrodynamics, heat and mass transfer and special features of semi fluidized bed reactor has been given by Murthy and Roy[1]. Semi fluidized beds can be operated either in a two phase or three phase mode. Of late more interest has been taken in three phase mode of operation.

**2.1 MODES OF OPERATION(three phase)**

Gas-liquid-solid fluidization can be classified mainly into four modes of operation. These modes are co-current three phase fluidization with liquid as the continuous phase (mode I-a), co-current three phase fluidization with gas as the continuous phase (mode I-b), inverse three phase fluidization (mode II-a), fluidization represented by a turbulent contact absorber (TCA) (mode II-b). Modes II-a and II-b are achieved with a counter-current flow of gas and liquid. Due to complex nature of three phase fluidization, however, various methods are possible in evaluating the operating and design parameters for each mode of operation.

Based on the differences in flow directions of gas and liquid and in contacting patterns between the particles and the surrounding gas and liquid, several types of operation for gas-liquid-solid fluidizations are possible. Three phase fluidization is divided into two types according to the relative direction of the gas and liquid flows, namely, co-current three phase fluidization and counter-current three phase fluidization [2].

In co-current three-phase fluidization, there are two contacting modes characterized by different hydrodynamic conditions between the solid particles and the surrounding gas and liquid. These modes are denoted as mode I-a (figure 2.2) and mode I-b (figure 2.1). Mode I-a defines co-current three phase fluidization with liquid as the continuous phase, while mode I-b defines co-current three phase fluidization with gas as the continuous phase. In mode I-a fluidization, the liquid with the gas forming discrete bubbles supports the particles. Mode I-a is generally referred to as gas-liquid fluidization. The term bubble flow, in Epstein's taxonomy [9], includes two types of flow for mode I-a namely, liquid- supported solids and bubble supported solids.

Counter-current three-phase fluidization with liquid as the continuous phase, denoted as mode II-a in figure: 2.1, is known as inverse three-phase fluidization. Counter-current three-phase fluidization with gas as the continuous phase, denoted as mode II-b in figure: 2.2, is known as a turbulent contact absorber, fluidized packing absorber, mobile bed, or turbulent bed contactor. In mode II-a operation the bed of particles with density lower than that of the liquid is fluidized by a downward liquid flow, opposite to the net buoyant force on the particles, while the gas introduced counter currently to that liquid forming discrete bubbles in the bed.

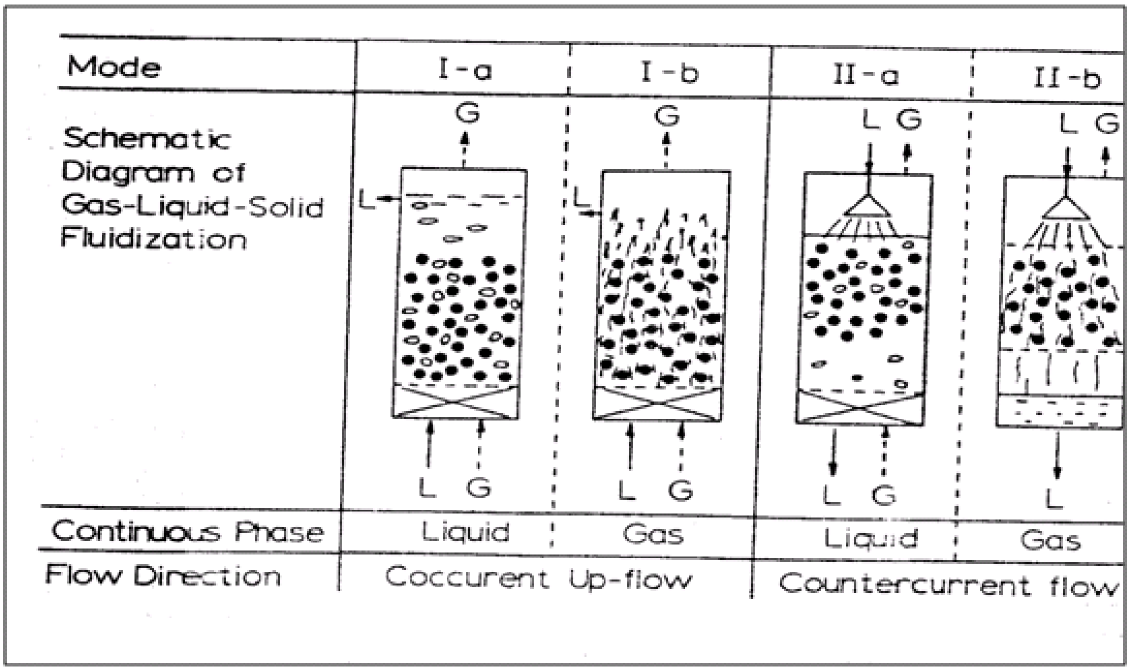


**Fig 2.1:** Modes of three phase fluidization

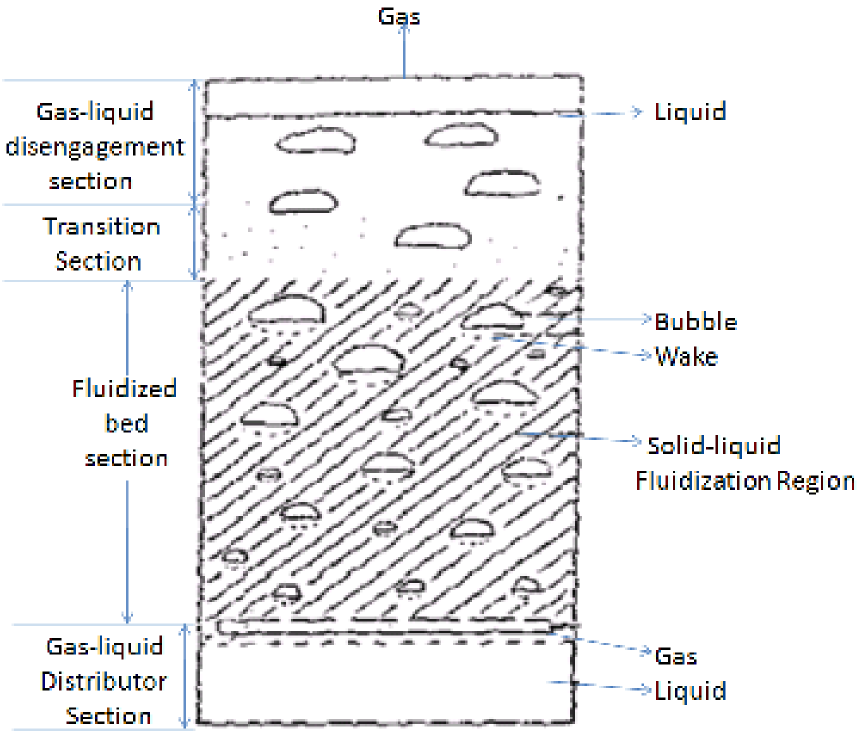


**Fig 2.2 :** Schematic representation of the Mode 1-a fluidized Bed Reactor

## 2.2 APPLICATIONS(two phase and three phase semi fluidized beds)

- Gas liquid solid fluidized bed had emerged in recent years as one of the most promising devices for 3 phase operations. Such devices are of considerable industrial importance as evidenced by their wide use in chemical, petrochemical and bio-chemical processing.
- The application of gas liquid solid fluidized bed system to bio-technological processes such as fermentation and aerobic waste water treatment has gained considerable importance in recent years.
- Application of semi fluidization in the fields of reaction kinetics has already been initiated. This technique is advantageous for fast exothermic reactions such as vapor phase oxidation and chlorination of hydrocarbons etc.
- Use of this technique in studies in mass transfer have shown that the magnitude of mass transfer coefficient can be controlled approx. linearly and within the limits of a completely fixed bed and completely fluidized bed by means of expansion alone.
- The application of semi fluidized beds has been broadly stressed by Fan and Hsu. According to them semi fluidized beds find wide applications as reactors for exothermic reactors and bioreactors in ion exchange and in filtration operation for the removal of suspended particles from gases and liquids.
- It is also widely used in industrial applications like drying, adsorption, reaction kinetics, solid catalyzed reactions, heat transfer etc.

## 2.3 PREVIOUS WORK

Little information is available on semi fluidization. Previous work relating to hydrodynamics study of two phase semi fluidized beds include that of Biswal et.al[6], Ho et.al[7] and Roy and Murthy[1].Jena et.al[4],[5],[8],[10] had carried out investigations relating to some hydrodynamic aspects like bed expansion, pressure drop, minimum and maximum liquid semi fluidization velocities for irregular, regular and cylindrical mono size particles in case of three phase semi fluidization.

While a few information are available on the two phase semi fluidization of binary mixtures and three phase semi fluidization of pure components, investigations relating to hydrodynamics of three phase fluidization of binary mixtures are almost absent. Therefore in present study hydrodynamic investigations viz. the pressure drop, minimum and maximum semi-fluidization velocity and rate of top packed bed formation in a co-current gas-liquid-solid three phase semi fluidized bed with binary homogeneous mixture using liquid as the continuous phase and gas as the discontinuous phase have been taken up.

## 2.4 PRESENT WORK

Fluidized bed and semi fluidized bed units are found in many plant operations in chemical, pharmaceutical, and mineral industries. Despite their widespread applications, much of the development and design of fluidized bed reactors have been empirical as the complex flow behaviors of gas-solid flow in these systems makes flow modelling a challenging task. The fundamental problem encountered in modelling hydrodynamics of fluidized bed is the motion of the two phases of which the interface is unknown and transient, and the interaction is understood only for a limited range of conditions.

The process engineer must have a good understanding of the factors that affect the behaviour of semi fluidized beds in order to use them effectively. Therefore, it is crucial that (s) he be able to predict how pressure drop will change under different fluidization and semi-fluidization conditions. The main concepts to be studied are the minimum semi fluidization velocity required for the bed of particles and the degree of pressure drop that the upward flowing fluid experiences. By being able to predict these properties, the engineer is able to design processes for industrial applications and find the best conditions to run the apparatus. The main objectives of this work are

- To determine the minimum liquid semi fluidization velocity, the bed pressure measurement has been done.
- Hydrodynamics characteristics especially the pressure drop of a co-current gas-liquid-solid semi fluidized bed have determined. For this the experimental work has performed.
- Also the effect of bed expansion with the static bed height and particle size is to be studied.
- The height of top packed bed formation is to be observed for calculating maximum semi fluidization velocity.

These have been done in order to develop a good understanding of each flow regime in gas-liquid and liquid-solid semi fluidization.

# CHAPTER 3

# EXPERIMENTAL

## 3.1 EXPERIMENTAL SET UP:

A schematic diagram of the experimental set up is shown in the **Figure 3.1.**The vertical Plexiglas fluidizer column is of 100 mm ID with a maximum height of 2m.The column consists of three sections, viz., the gas-liquid disengagement section, test section, and gas-liquid distributor section. Water and air is used as the liquid and gas phases respectively.

### 1.Gas-Liquid Disengagement Section

Gas-Liquid Disengagement Section is at the top of the column, which allows gas to escape and liquid to be circulated. Any entrained particles retain on the screen attached to the top of this section.

### 2. Test Section

The test/study section is in between the gas-liquid disengagement section and gas-liquid distributor Section. The gas-liquid flow is co-current and upwards. The whole test is performed in this section. All the pressure taps are connected to this section.

### 3. Gas-Liquid Distributor Section

The gas-liquid distributor is located at the bottom of the test section and is designed in such a manner that uniform distribution of the liquid and gas can be maintained in the column Liquid and gas inlets are connected to this section. This is an important component of the setup. It is a perforated plate made of G.I. sheet of I mm thick, 120 mm diameter. About 278 numbers of 2, 2.5 and 3mm pores are randomly placed in the sheet **(Figure: 3.2)**. A screen is placed just above the sheet to avoid the flow of bed materials in to the calming section. Two numbers of gaskets of 3mm thick and 150mm dia. are provided between the flange and the screen. The distribution is on integral part of calming section where it is followed by a conical section **(Figure: 3.3)**.The height of perpex conical section is 12 cm. There is a gas distributor consists of 50 numbers of 2 and 3mm pores placed randomly. In this section the gas and liquid streams merged and passed through the perforated grid. The mixing section and grid ensure that the gas and liquid are well mixed and evenly distributed into the bed.

**4. Pressure Taps**

The column is equipped with twenty one pressure taps. Three taps each in gas-liquid disengagement section and Gas-liquid distributor Section, fifteen in test section. These are installed at equal intervals of 30 cm and connected to the manometers.

**5. Rotameter**

There are one lower range (0-10 lpm) and two higher range (0-100, 0-200lpm) calibrated rotameter for measurement of liquid and gas flow rates.

**6. Air Compressor**

It is a multistage compressor (3 Phase, 1 HP, 1440rpm). It consists of a receiver, which receives compressed air from the compressor and an air accumulator/constant pressure tank. The tank is a horizontal cylinder used for storing the compressed air. The purpose of air accumulator/ constant pressure tank is to dampen any pressure fluctuation. The silica gel tower absorbs the moisture carried out by the air from the air accumulator. The moisture and oil free compressed air is fed to the fluidizer through the calibrated rotameter.

**7. Liquid Pump**

A centrifugal pump (Single phase, 1HP, and 2900rpm) is used for delivering liquid to the fluidizer through the calibrated rotameter.

**8. Liquid Reservoir**

There is a liquid reservoir (42X32X70cm3) installed at the base of the column. The main purpose of this liquid reservoir is to store the bypass and recycled liquid.

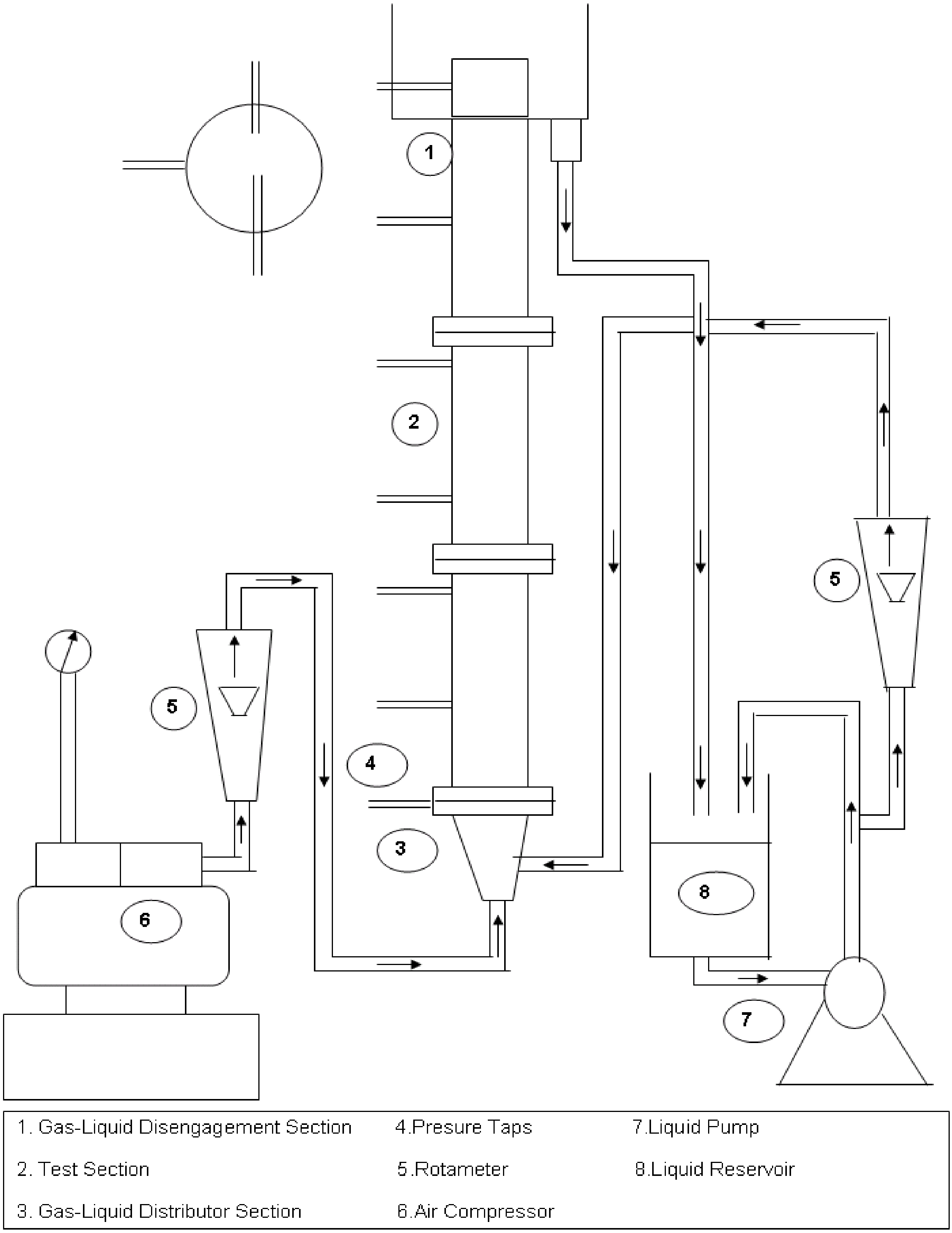


**Fig 3.1** A schematic diagram of the experimental set up

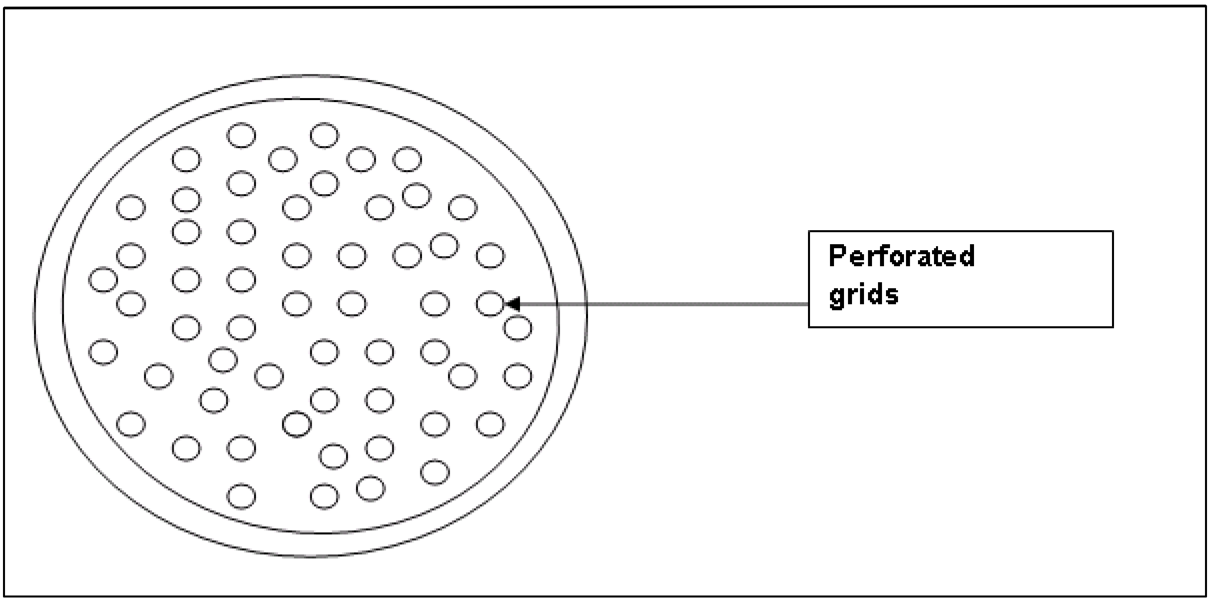


**Fig 3.2** A structure for perforated grid plate

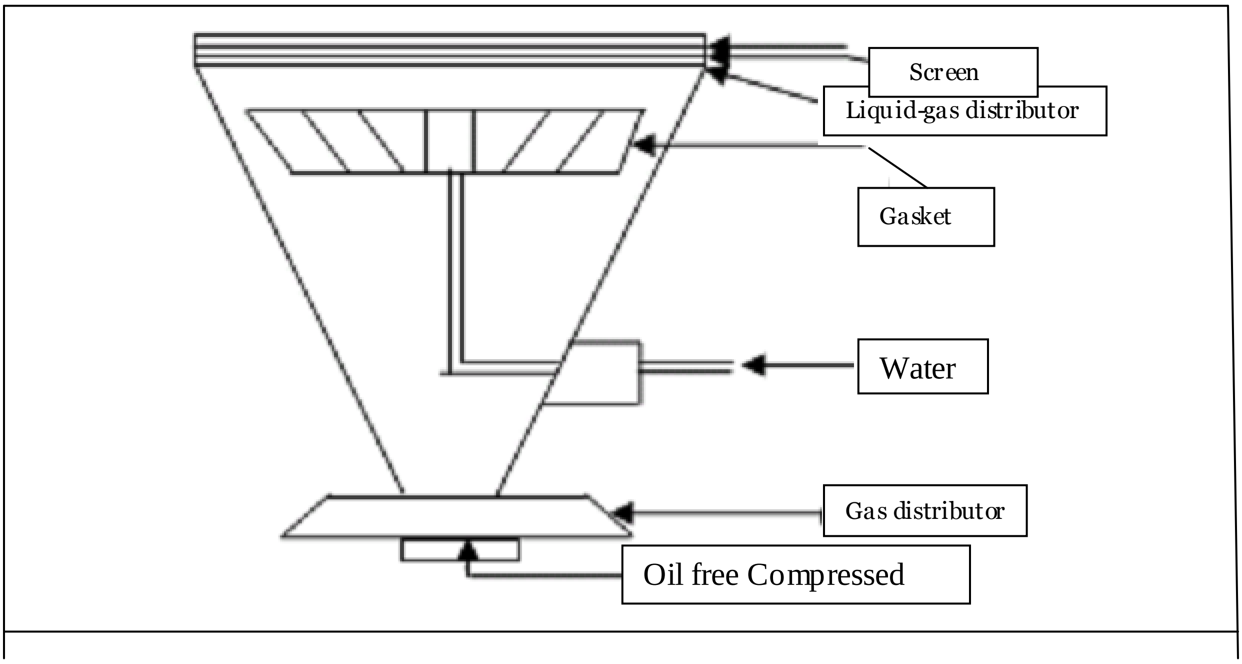


**Fig 3.3** Schematic diagram of conical section

### 3.1.2 EXPERIMENTAL PROCEDURE

The three phases present in the column were 1.7 and 2.31 mm dolomite, tap water and the oil free compressed air. The air-water flow were co-current and upwards. Accurately weighed amount of material was fed into the column and adjusted for a specified initial static bed height. Water was pumped to the fluidizer at a desired flow rate. Then air was injected into the column through the air distributor. Approximately five minutes was allowed to make sure that the steady state was reached. Then the readings of each manometer were taken. Also, the bed expansion was noted. The values of minimum semi fluidization velocity for every run have been obtained by plotting pressure drop across the beds versus liquid flow rates at constant air flow rates. Maximum semi fluidization velocity is predicted from the extrapolation of the plot of Hpa/Hs.

### PRECAUTIONS

- Care should be taken in using the vents otherwise there may be the chance of air bubbles in the manometer tubes, which will affect the readings.
- There should be no leakage in the pipe lines.
- There should be no fluctuations in water and air flow rates. The temperature of water should be kept at constant by exchanging with cold water. So at each set of readings the temperature should be noted.
- The maximum and minimum bed height should be taken correctly.
- For every break if the original levels in manometers have not seen, then make the level by adjusting the vents.

## 3.2 SCOPE OF EXPERIMENTS AND PROPERTIES OF MATERIALS

### 3.2.1 Properties of Bed Materials

| Sl. No. | Materials | Mesh size | $d_p$,mm | $\rho_p$ (kg.m$^{-3}$) |
|---|---|---|---|---|
| 01 | dolomite | -6+7 | 2.31 | 2,652 |
| 02 | dolomite | -7+8 | 1.7 | 2,652 |

### 3.2.2 Properties of Fluidizing Medium

| Medium | $\rho$ (kg.m$^{-3}$) | $\mu$ (Ns/m$^2$) |
|---|---|---|
| Air at 25$^0$C | 1.168 | 0.00187 |
| Water at 25$^0$C | 1,000 | 0.095 |

### 3.2.3 Properties of Manometric Fluid

| | $\rho$ (gm/cc) | $\mu$ (Ns/m$^2$) |
|---|---|---|
| Mercury | 13.6 | 0.15 |

### 3.2.4 Scope of experiments

| | | | | |
|---|---|---|---|---|
| Static bed height(cm), $H_s$ | 10 | 15 | 20 | 25 |
| Mixture composition | 50:50 | 60:40 | 70:30 | 80:20 |
| Mean diameter(cm) | 0.179 | 0.185 | 0.19 | 0.195 |
| Expansion Ratio,R | 2 | 3 | 3.5 | 4 |

### 3.3 EXPERIMENTAL DATA

For Hs=10cm and R=3 and 50:50 mixture of material

**Table 3.3.1 :**Variation of pressure drop with liquid flow rate at constant gas flow rate

| Liquid velocity (m/s) | Gas velocity (m/s) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0.006 | | 0.0106 | | 0.0148 | | 0.0212 | |
| | Pressure drop (KPa) | $H_{pa}$ (cm) | Pressure drop (KPa) | $H_{pa}$ (cm) | Pressure drop (KPa) | $H_{pa}$ (cm) | Pressure drop (KPa) | $H_{pa}$ (cm) |
| 0.004246 | 3.708 | 0 | 6.18 | 0 | 7.42 | 0 | 7.42 | 0 |
| 0.012739 | 4.944 | 0 | 6.79 | 0 | 8.65 | 0 | 8.03 | 0 |
| 0.021231 | 5.562 | 0 | 7.41 | 0 | 9.27 | 0 | 8.65 | 0 |
| 0.033970 | 5.562 | 0 | 7.41 | 0 | 9.88 | 0 | 8.65 | 0 |
| 0.047710 | 5.562 | 0 | 7.41 | 0 | 9.88 | 0 | 8.65 | 0 |
| 0.053079 | 5.933 | 0.4 | 7.66 | 0.2 | 9.88 | 0 | 9.27 | 0.8 |
| 0.063694 | 6.180 | 1.0 | 8.03 | 0.8 | 10.13 | 0.5 | 9.88 | 1.0 |
| 0.084926 | 6.427 | 1.8 | 8.65 | 2.0 | 10.51 | 2.0 | 10.50 | 2.5 |
| 0.106517 | 6.551 | 3.0 | 9.27 | 4.0 | 11.12 | 4.0 | 11.12 | 5.0 |

**Table 3.3.2:** Variation of pressure drop with gas flow rate at constant liquid flow rates

| Gas velocity (m/s) | Liquid velocity (m/s) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0.0424 | | 0.0636 | | 0.0743 | | 0.0848 | |
| | Pressure drop (KPa) | $H_{pa}$ (cm) | Pressure drop (KPa) | $H_{pa}$ (cm) | Pressure drop (KPa) | $H_{pa}$ (cm) | Pressure drop (KPa) | $H_{pa}$ (cm) |
| 0.0089 | 4.939 | 0 | 6.790 | 0 | 7.16 | 0 | 7.400 | 0 |
| 0.0106 | 5.556 | 0 | 6.910 | 0 | 7.65 | 0 | 7.400 | 0 |
| 0.0148 | 5.927 | 0 | 7.160 | 0 | 8.02 | 0 | 7.400 | 0 |
| 0.0212 | 6.174 | 0 | 7.408 | 0 | 8.02 | 0 | 9.631 | 2 |
| 0.0318 | 6.174 | 0 | 7.408 | 0 | 8.02 | 0 | 9.878 | 3 |
| 0.0424 | 6.421 | 0.5 | 8.020 | 0.5 | 8.30 | 0.8 | 10.490 | 4 |
| 0.0531 | 7.038 | 1.0 | 8.640 | 1 | 8.64 | 1.5 | | |
| 0.0637 | 8.396 | 2.0 | 9.014 | 2 | 9.014 | 2.5 | | |

For Hs=15cm and R=2 and 50:50 mixture of material

**Table 3.3.3** : Variation of pressure drop with liquid flow rate at constant gas flow rate

| Liquid velocity (m/s) | Gas velocity (m/s) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0.0106 | | 0.0148 | | 0.0212 | | 0.0318 | |
| | Pressure drop (KPa) | $H_{pa}$ (cm) | Pressure drop (KPa) | $H_{pa}$ (cm) | Pressure drop (KPa) | $H_{pa}$ (cm) | Pressure drop (KPa) | $H_{pa}$ (cm) |
| 0.004200 | 2.470 | 0 | 2.47 | 0 | 2.47 | 0 | 2.470 | 0 |
| 0.021231 | 3.708 | 0 | 4.32 | 0 | 4.32 | 0 | 4.326 | 0 |
| 0.042463 | 4.944 | 0 | 5.19 | 0 | 5.19 | 0 | 5.560 | 0 |
| 0.063694 | 6.180 | 0 | 6.79 | 0 | 6.79 | 0 | 7.040 | 0 |
| 0.074310 | 6.180 | 0 | 6.79 | 0 | 6.79 | 0 | 7.040 | 0 |
| 0.084926 | 6.180 | 2 | 6.79 | 0 | 6.79 | 0 | 7.040 | 0 |
| 0.095541 | 6.550 | 5 | 7.41 | 7 | 7.41 | 5 | 7.300 | 8 |
| 0.106157 | 6.790 | 8 | 8.03 | 9 | 8.03 | 8 | 8.030 | 10 |
| 0.122801 | 7.410 | 10 | 8.13 | 11 | 8.23 | 11.2 | 8.330 | 12 |

**Table 3.3.4:** Variation of pressure drop with gas flow rate at constant liquid flow rate

| Gas velocity (m/s) | Liquid velocity (m/s) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0.0424 | | 0.0636 | | 0.0848 | | 0.1060 | |
| | Pressure drop (KPa) | $H_{pa}$ (cm) | Pressure drop (KPa) | $H_{pa}$ (cm) | Pressure drop (KPa) | $H_{pa}$ (cm) | Pressure drop (KPa) | $H_{pa}$ (cm) |
| 0.0089 | 2.47 | 0 | 2.47 | 0 | 2.47 | 0 | 3.09 | 0 |
| 0.0106 | 2.84 | 0 | 3.09 | 0 | 2.82 | 0 | 3.58 | 0 |
| 0.0148 | 3.09 | 0 | 3.46 | 0 | 3.09 | 0 | 3.71 | 0 |
| 0.0212 | 3.46 | 0 | 3.71 | 0 | 3.46 | 0 | 3.71 | 0 |
| 0.0318 | 3.46 | 0 | 3.71 | 0 | 3.46 | 0 | 3.955 | 4 |
| 0.0424 | 3.58 | 3 | 3.83 | 4 | 3.58 | 3 | 4.69 | 6 |
| 0.0531 | 3.7 | 5 | 4.33 | 6 | 3.71 | 5 | 5.56 | 10 |
| 0.0637 | 4.32 | 6.5 | 4.69 | 8 | 4.32 | 6.5 | 6.78 | 12 |

Similar procedure is repeated for expansion ratios of 3, 3.5, 4 and for different static bed heights of 20cm, 25cm.

## 3.4 RESULTS AND DISCUSSION

**Pressure drop and minimum semi fluidization velocity:**

The minimum semi fluidization velocity is defined as the fluid velocity at which top of the fluidized bed just touches the top restraint. The plot of superficial liquid velocity against pressure drop gives a break which corresponds to minimum liquid semi fluidization velocity.

For static bed height of 15 cm and 50:50 mixture and expansion ratio R=2

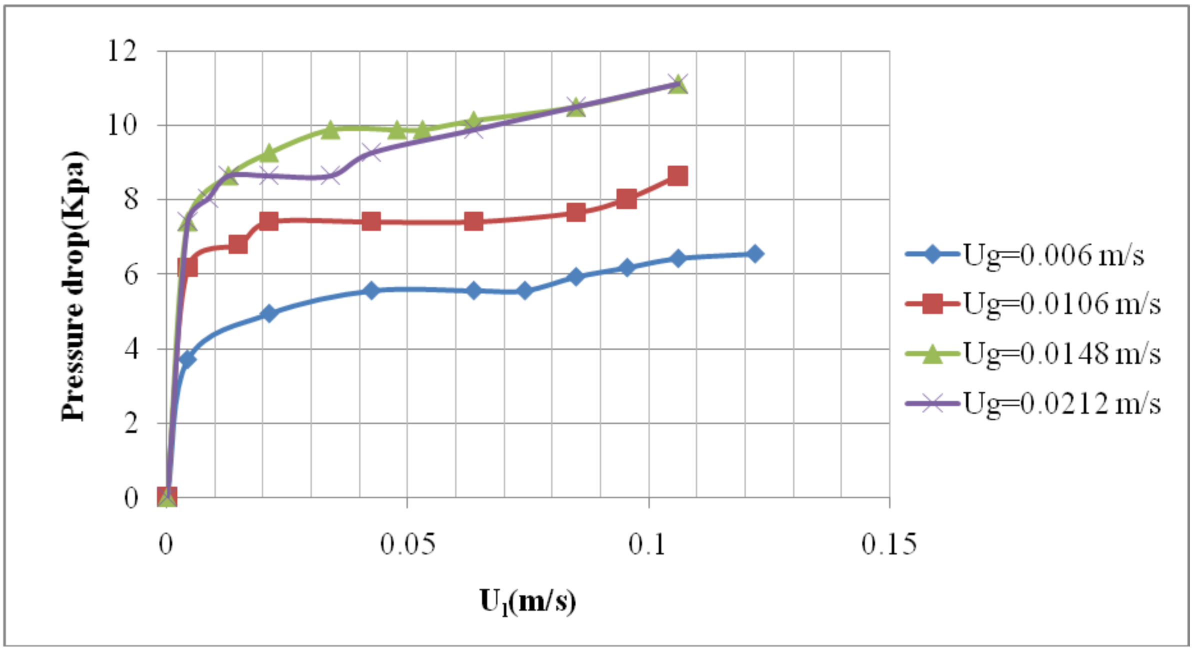


Fig **3.4.1:** Variation of bed pressure drop with superficial liquid velocity at different superficial gas velocities

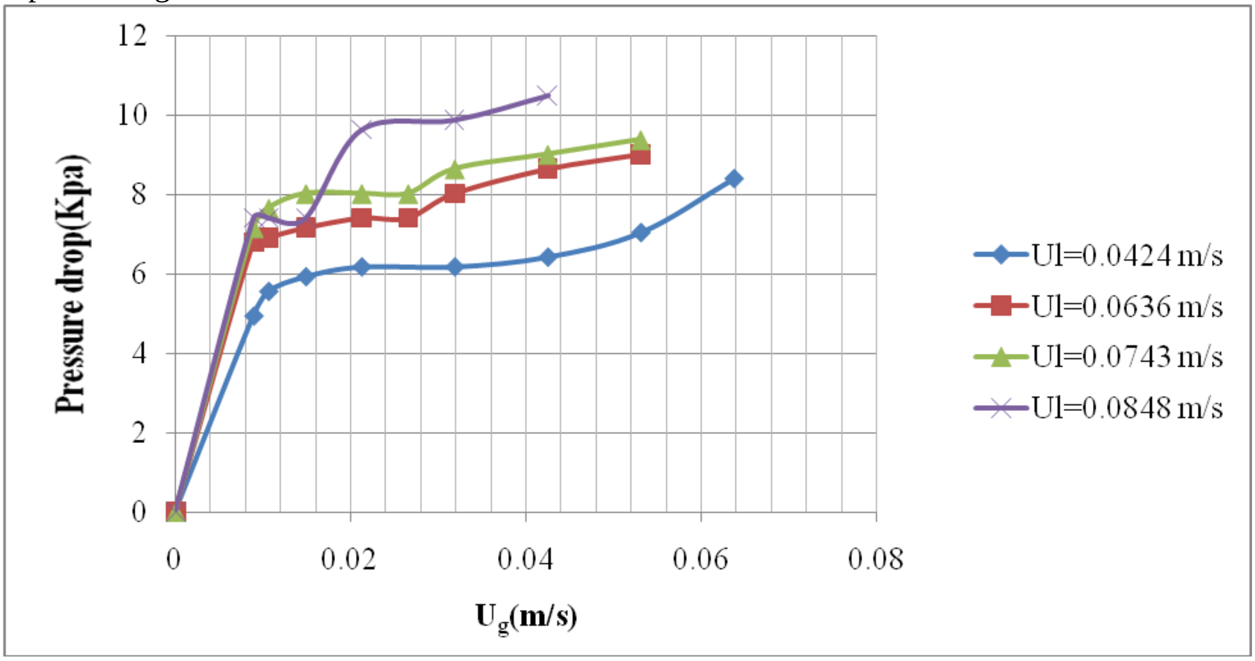


**Fig 3.4.2:** Variation of bed pressure drop with superficial gas velocities at different superficial liquid velocities

For static bed height of 15 cm and 50:50 mixture

(For expansion ratio **R=2**)

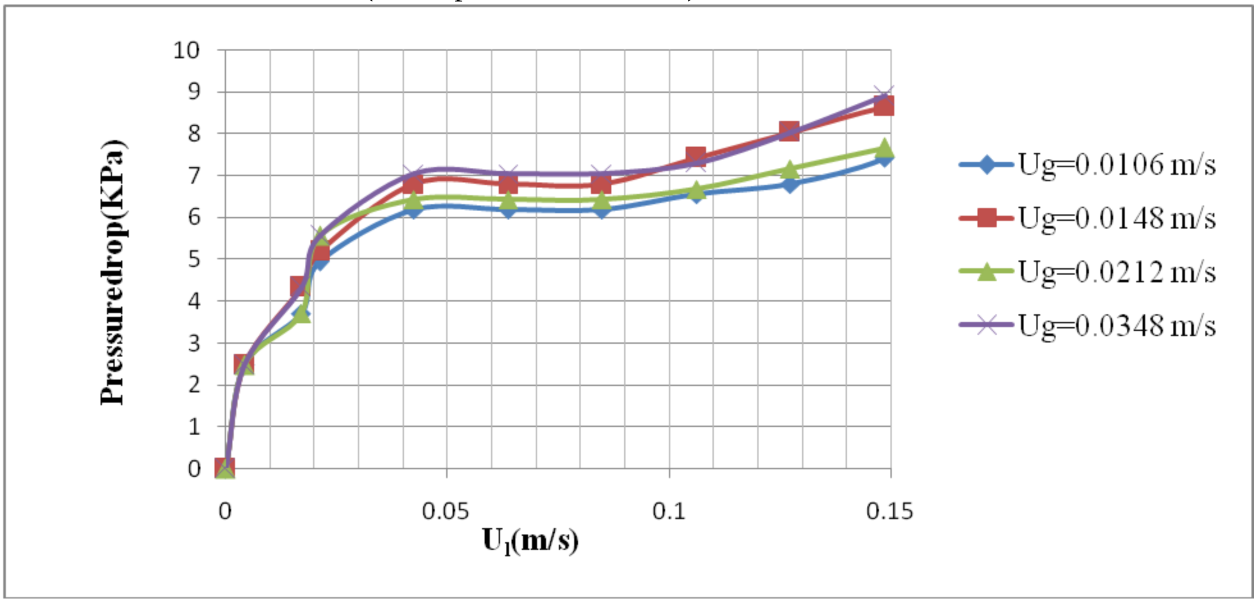


**Fig 3.4.3:** Variation of bed pressure drop with superficial liquid velocity at different superficial gas velocities

(For expansion ratio **R=3**)

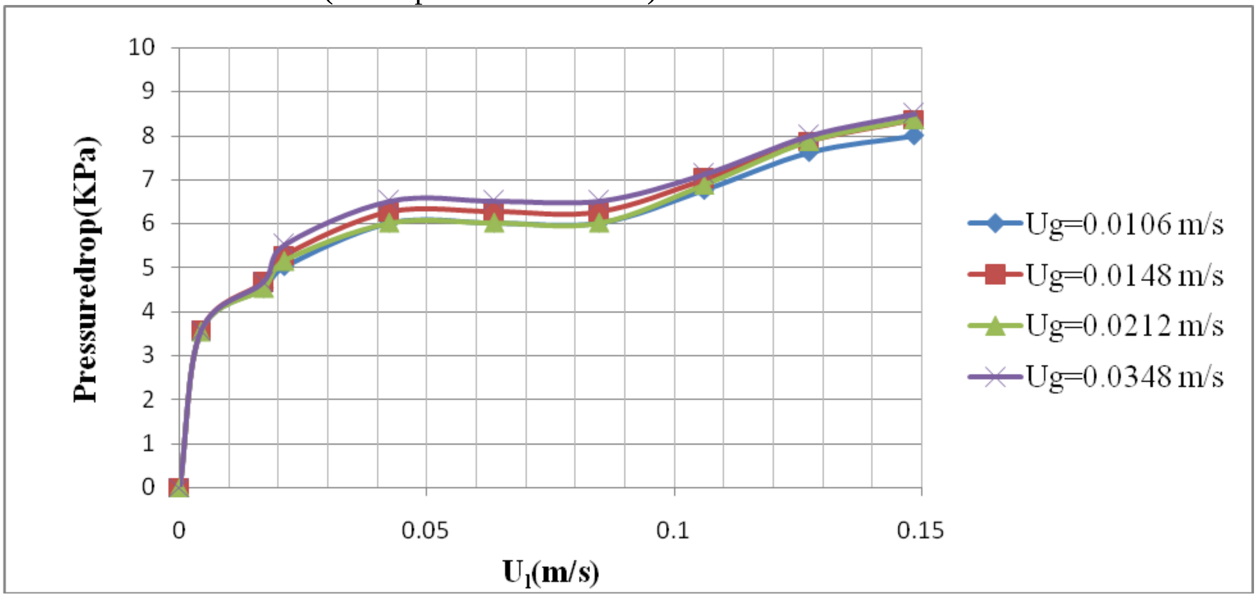


**Fig 3.4.4:** Variation of bed pressure drop with superficial liquid velocity at different superficial gas velocities

(For expansion ratio **R=3.5**)

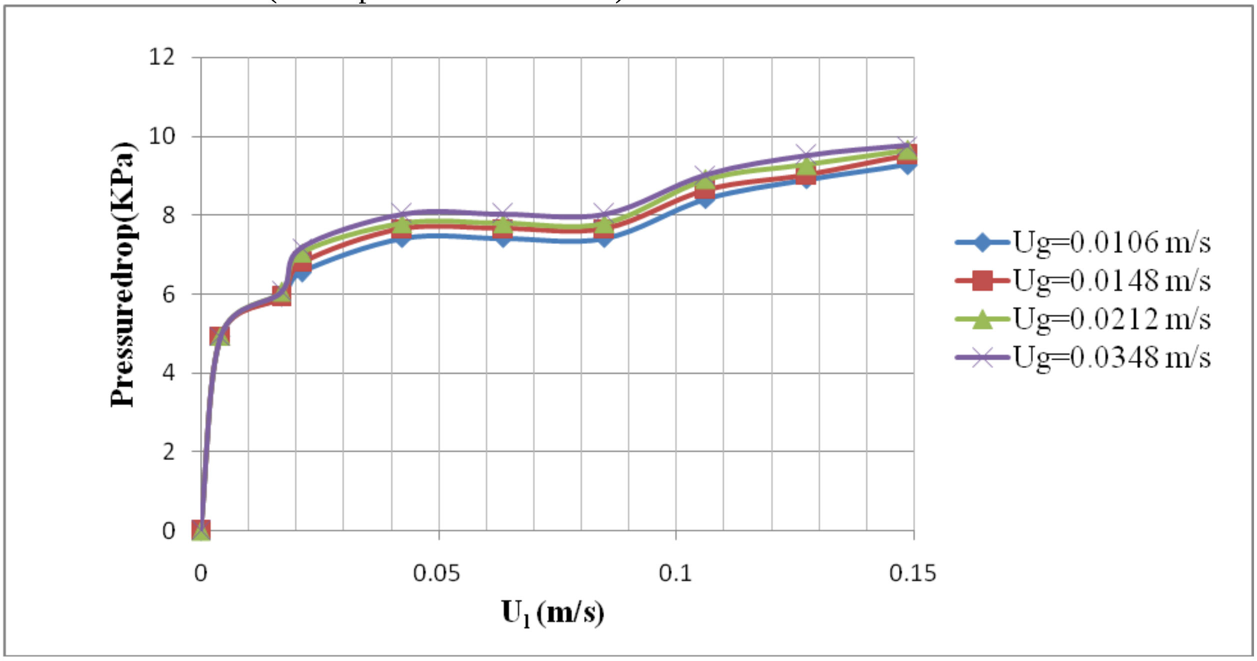


**Fig 3.4.5:** Variation of bed pressure drop with superficial liquid velocity at different superficial gas velocities

(For expansion ratio **R=4**)

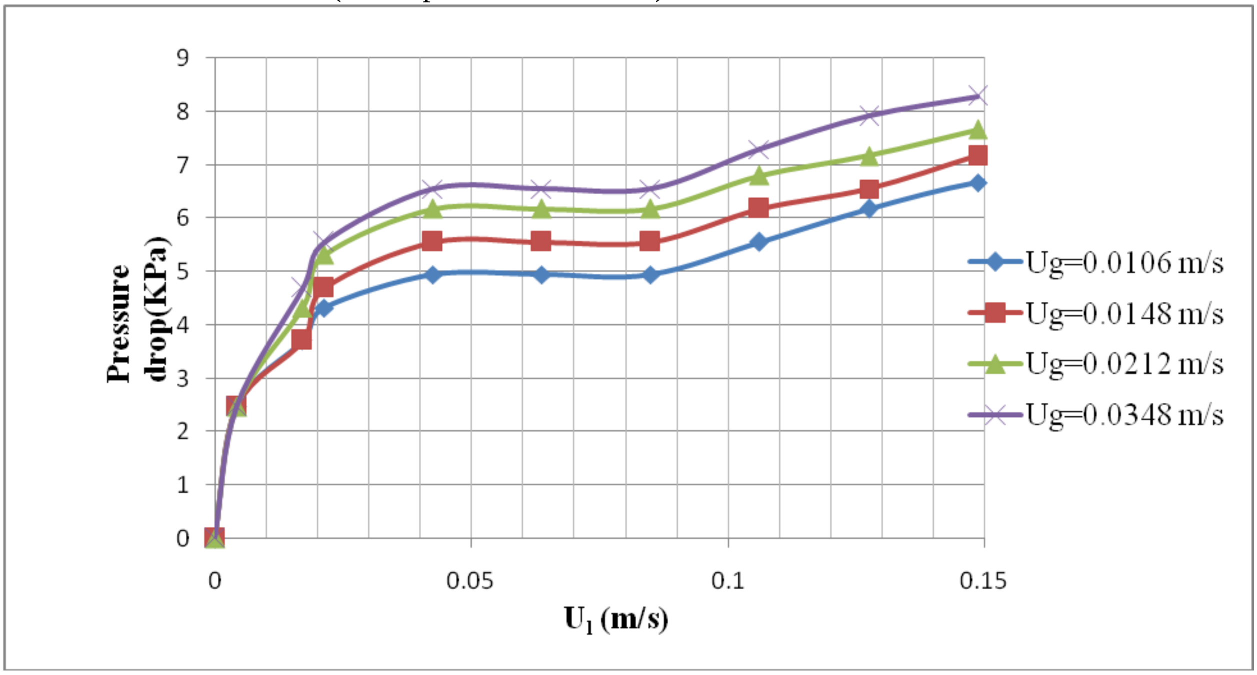


**Fig 3.4.6:** Variation of bed pressure drop with superficial liquid velocity at different superficial gas velocities

For static bed height of 20 cm and For expansion ratio **R=3**

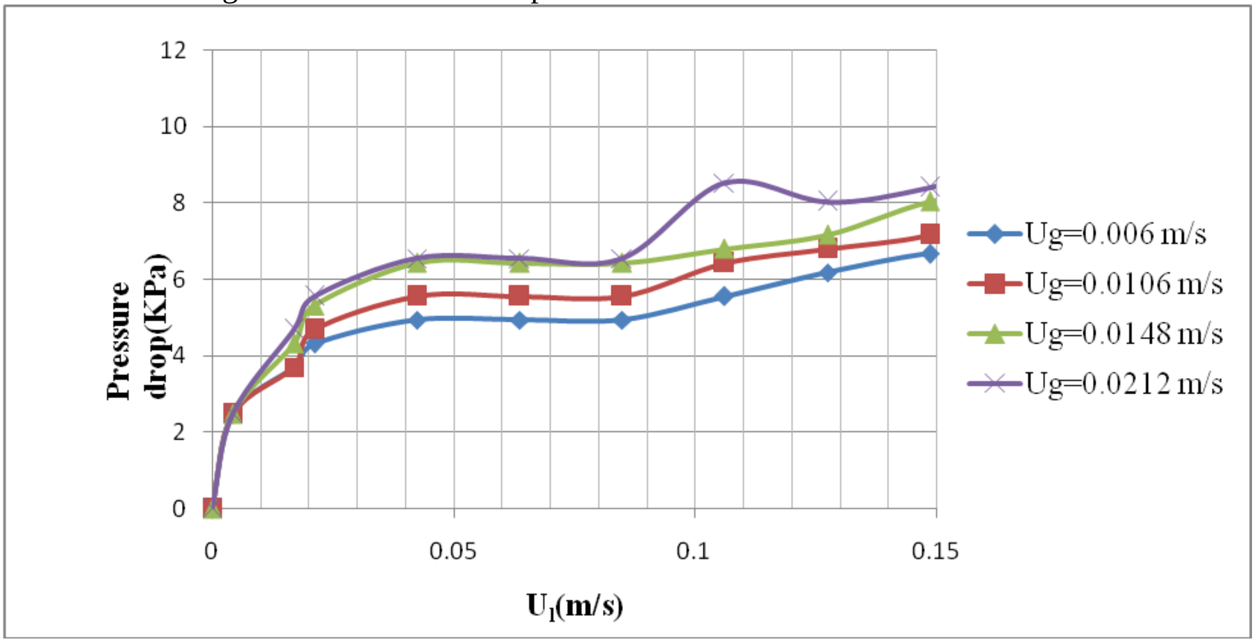


**Fig 3.4.7:** Variation of bed pressure drop with superficial liquid velocity at different superficial gas velocities

For static bed height of 25 cm and for expansion ratio **R=3**

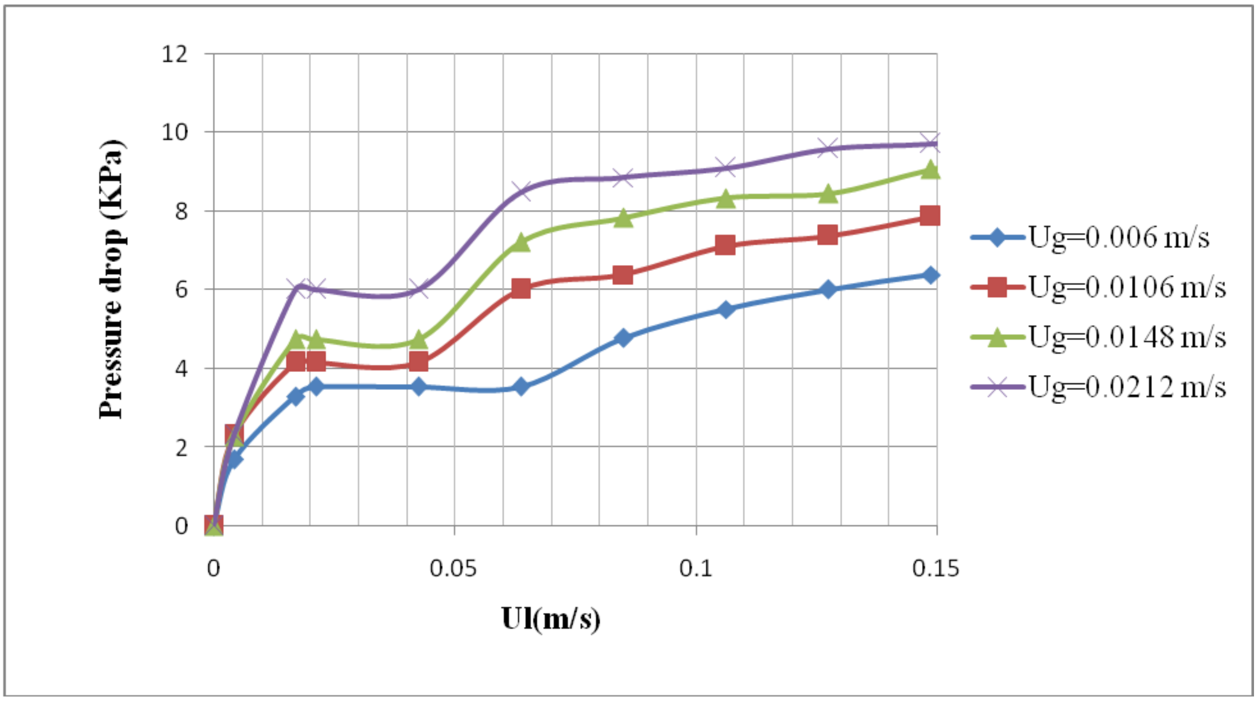


**Fig 3.4.8:** Variation of bed pressure drop with superficial liquid velocity at different superficial gas velocities

The hydrodynamic study of the three phase semi fluidized bed with irregular particles reveals that the minimum liquid semi fluidization velocity decreases with gas velocity and pressure drop is found to increase with superficial gas velocity for a fixed liquid superficial velocity.

**Height of top packed bed and maximum liquid semi fluidization velocity:**

Due to arrest of the free expansion of the fluidized bed by top retaining grid a packed bed is formed at the top. In two phase system there exists a clear zone in between top packed bed and bottom fluidized bed which almost devoid of particles. This phenomenon is not observed in three phase fluidization, but the concentration of the particles remains low in this region. This is due to discontinuous motion of the gas bubbles in the bed. The rate of formation of packed bed is expressed as the ratio of packed bed height ($H_{pa}$) to the initial static bed height($H_s$). The liquid velocity at which all the solid particles are supported by fluid in top packed bed at a constant gas velocity is called maximum liquid semi fluidization velocity, which can be obtained by extrapolation of the plot of Hpa/Hs to the value of 1.

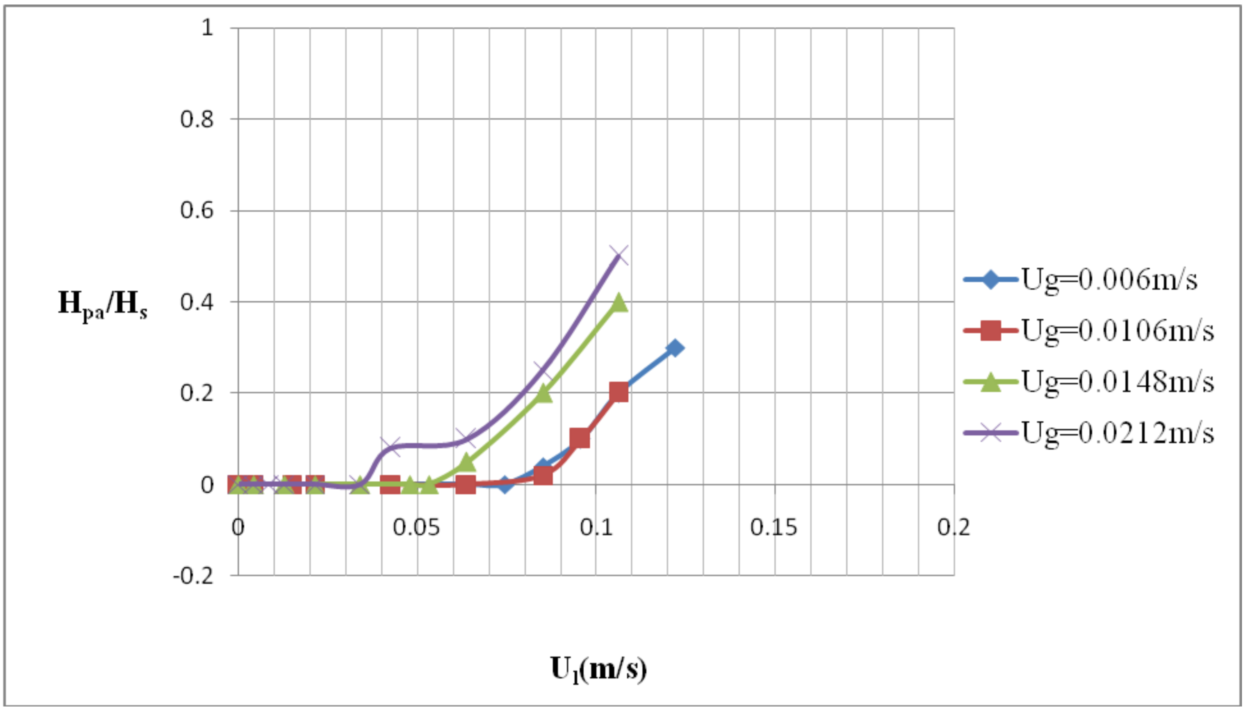


**Fig 3.4.9:** Variation of $H_{pa}/H_s$ with $U_l$ at different $U_g$

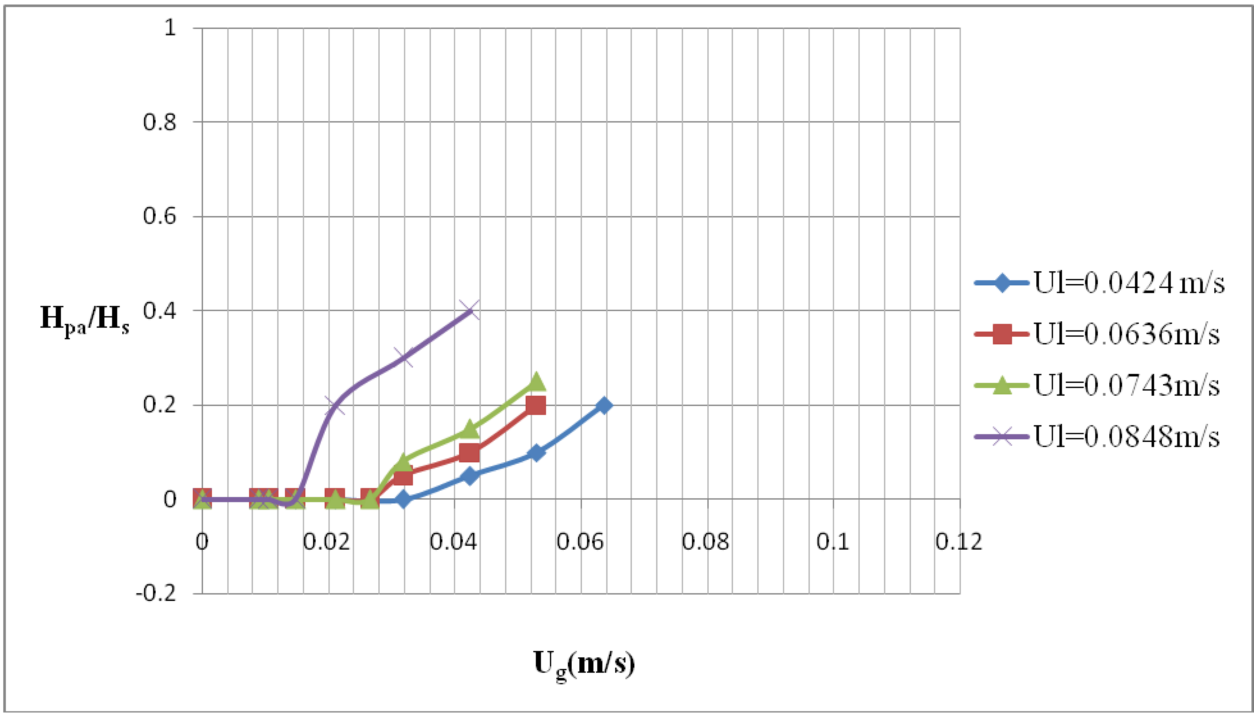


**Fig 3.4.10:** Variation of $H_{pa}/H_s$ with Ug at different $U_l$

(For expansion ratio **R=2**)

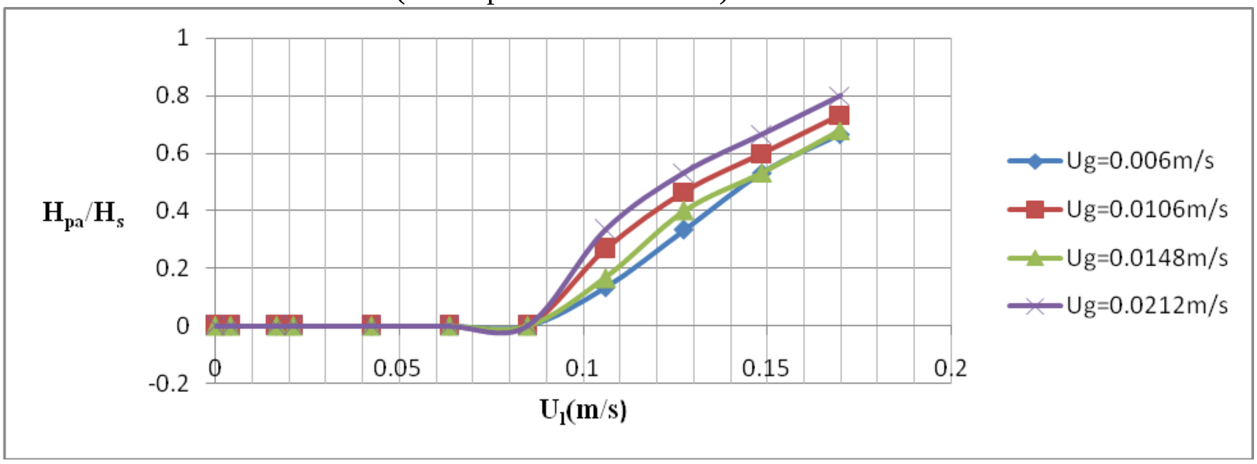


**Fig 3.4.11:** Variation of $H_{pa}/H_s$ with $U_l$ at different $U_g$

(For expansion ratio **R=3**)

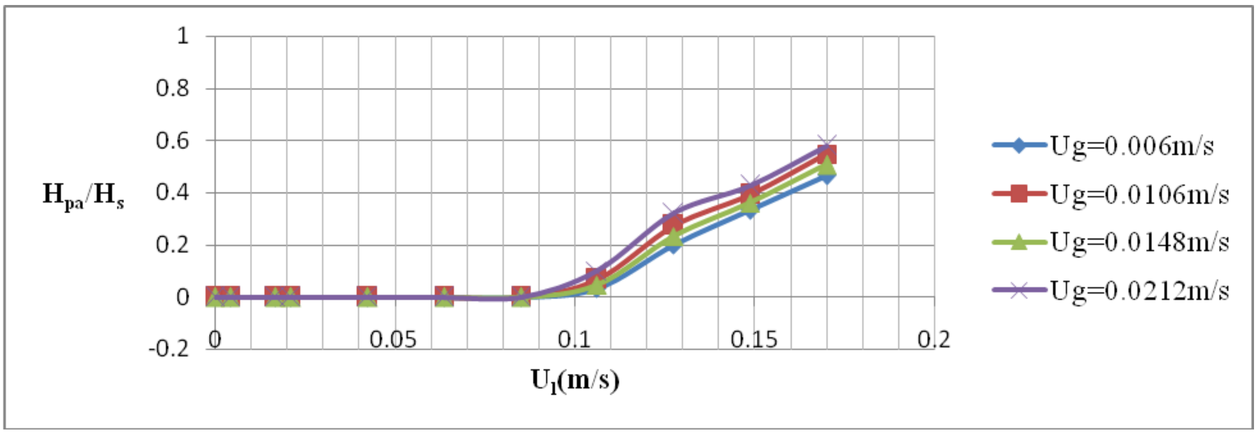


**Fig 3.4.12:** Variation of $H_{pa}/H_s$ with $U_l$ at different $U_g$

(For expansion ratio **R=3.5**)

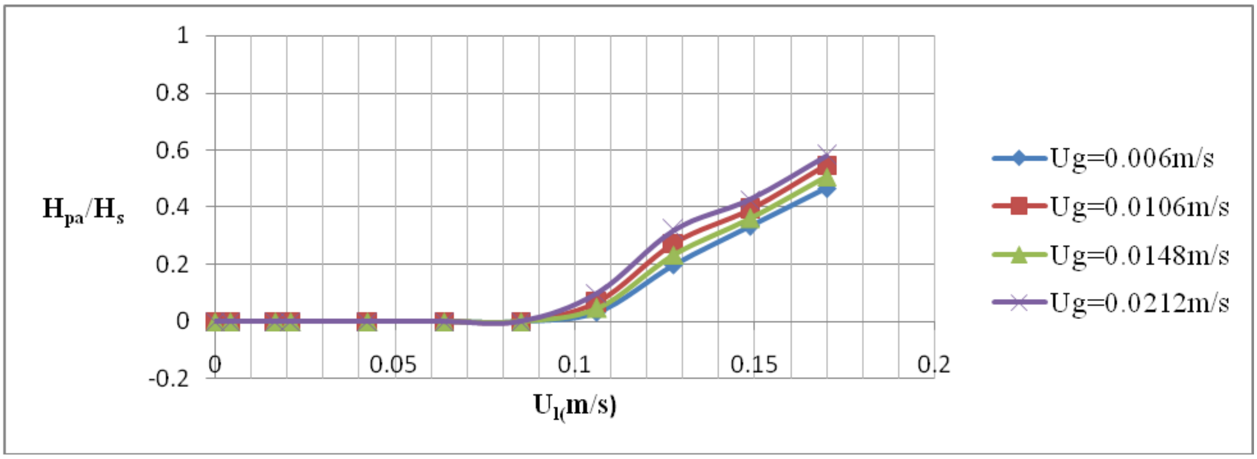


**Fig 3.4.13:** Variation of $H_{pa}/H_s$ with $U_l$ at different $U_g$

(For expansion ratio **R=2**)

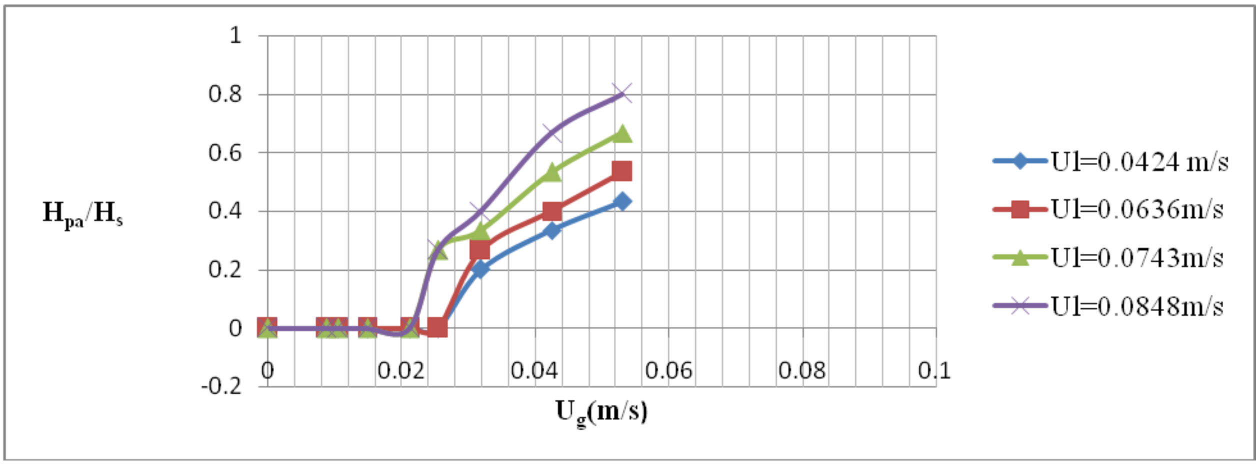


**Fig 3.4.14:** Variation of Hpa/Hs with Ug at different $U_l$

(For expansion ratio **R=3.5**)

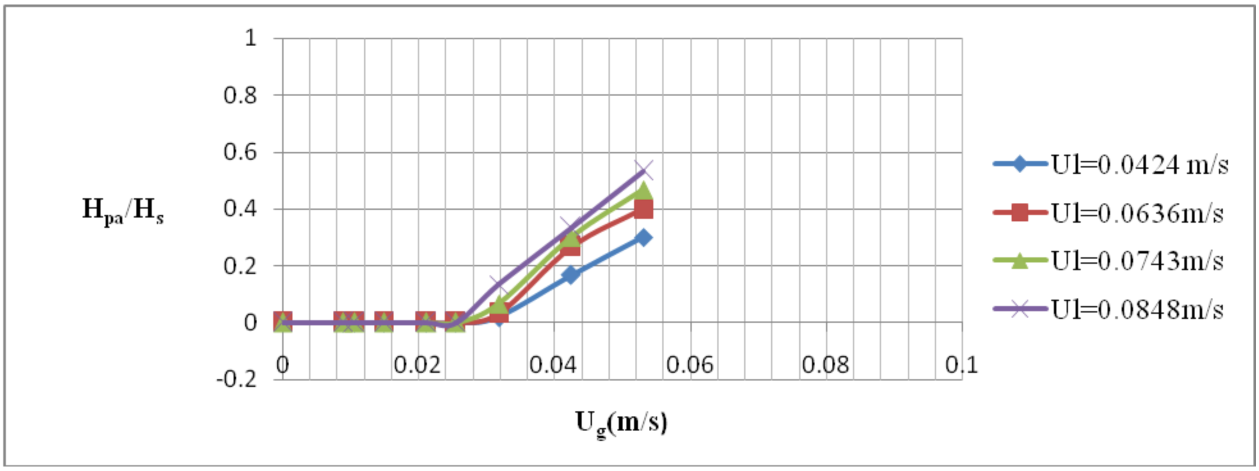


**Fig 3.4.15:** Variation of $H_{pa}/H_s$ with $U_g$ at different $U_l$

(For expansion ratio **R=4**)

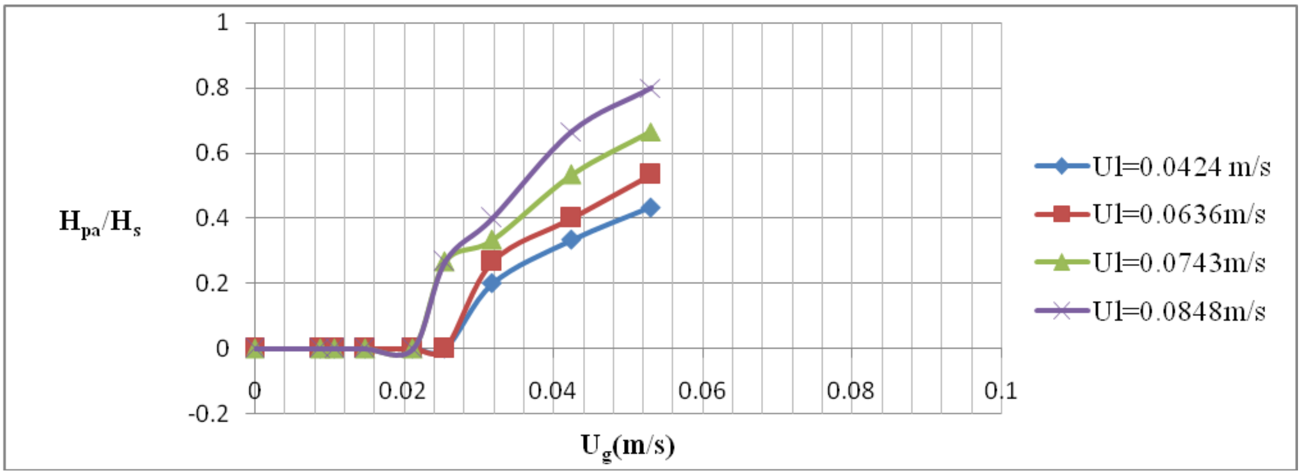


**Fig 3.4.16:** Variation of $H_{pa}/H_s$ with $U_g$ at different $U_l$

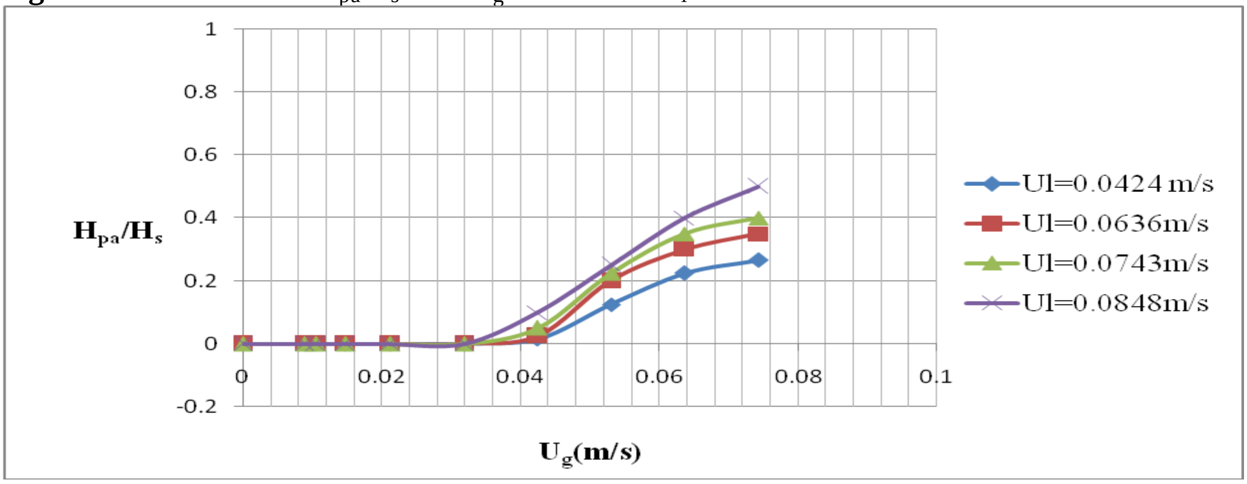


**Fig 3.4.17:** Variation of $H_{pa}/H_s$ with $U_g$ at different $U_l$

Hpa/Hs increases with gas and liquid superficial velocity. The maximum liquid semi fluidization velocity decreases with gas superficial velocity.

- For static bed height 10cm and expansion ratio R=2 and 50:50 mixture

**Table 3.4.1:** Min. and Max. semi-fluidization velocities at constant gas and liquid flow rates

| For constant gas flow rate | | | For constant liquid flow rate | | |
|---|---|---|---|---|---|
| $U_g$(m/s) | $U_{lmsf}$ (m/s) (From Plot3.1) | $U_{lMsf}$ (m/s) (From Plot3.3) | $U_l$(m/s) | $U_{gmsf}$(m/s) (From Plot3.2) | $U_{gMsf}$(m/s) (From Plot3.2) |
| 0.006 | 0.08 | 0.18 | 0.0424 | 0.042 | 0.12 |
| 0.0106 | 0.07 | 0.17 | 0.0636 | 0.035 | 0.11 |
| 0.0148 | 0.06 | 0.14 | 0.0743 | 0.03 | 0.09 |
| 0.0212 | 0.04 | 0.12 | 0.0848 | 0.0185 | 0.08 |

❖ For static bed height 15cm and for 50:50 mixture for different expansion ratios

**Table 3.4.2:** Min. and Max. liquid semi-fluidization velocities at constant gas flow rates

| $U_g$(m/s) | R=2 | | R=3 | | R=3.5 | | R=4 | |
|---|---|---|---|---|---|---|---|---|
| | $U_{lmsf}$ (m/s) | $U_{lMsf}$ (m/s) | $U_{lmsf}$ (m/s) | $U_{lMsf}$ (m/s) | $U_{lmsf}$ (m/s) | $U_{lMsf}$ (m/s) | $U_{lmsf}$ (m/s) | $U_{lMsf}$ (m/s) |
| 0.0106 | 0.044 | 0.18 | 0.048 | 0.19 | 0.050 | 0.20 | 0.055 | 0.20 |
| 0.0148 | 0.040 | 0.17 | 0.041 | 0.18 | 0.042 | 0.19 | 0.050 | 0.18 |
| 0.0212 | 0.035 | 0.16 | 0.038 | 0.16 | 0.040 | 0.17 | 0.045 | 0.17 |
| 0.0348 | 0.029 | 0.15 | 0.030 | 0.15 | 0.038 | 0.16 | 0.040 | 0.16 |

**Table 3.4.3:** Min. and Max. gas semi-fluidization velocities at constant liquid flow rates

❖ For static bed height 20cm and expansion ratio R=3 and 50:50 mixture

| $U_l$(m/s) | R=2 | | R=3 | | R=3.5 | | R=4 | |
|---|---|---|---|---|---|---|---|---|
| | $U_{gmsf}$ (m/s) | $U_{gMsf}$ (m/s) | $U_{gmsf}$ (m/s) | $U_{gMsf}$ (m/s) | $U_{gmsf}$ (m/s) | $U_{gMsf}$ (m/s) | $U_{gmsf}$ (m/s) | $U_{gMsf}$ (m/s) |
| 0.0424 | 0.048 | 0.080 | 0.050 | 0.085 | 0.050 | 0.088 | 0.055 | 0.090 |
| 0.0636 | 0.045 | 0.075 | 0.045 | 0.078 | 0.048 | 0.080 | 0.050 | 0.080 |
| 0.0848 | 0.042 | 0.068 | 0.043 | 0.070 | 0.045 | 0.072 | 0.045 | 0.075 |
| 0.1060 | 0.040 | 0.065 | 0.042 | 0.065 | 0.043 | 0.068 | 0.040 | 0.070 |

**Table 3.4.4:** Min. and Max. semi-fluidization velocities at constant gas and liquid flow rates

| For constant gas flow rate | | | For constant liquid flow rate | | |
|---|---|---|---|---|---|
| $U_g$(m/s) | $U_{lmsf}$ (m/s) | $U_{lMsf}$ (m/s) | $U_l$(m/s) | $U_{gmsf}$(m/s) | $U_{gMsf}$(m/s) |
| 0.0106 | 0.050 | 0.20 | 0.0424 | 0.050 | 0.088 |
| 0.0148 | 0.042 | 0.19 | 0.0636 | 0.048 | 0.080 |
| 0.0212 | 0.040 | 0.17 | 0.0848 | 0.045 | 0.072 |
| 0.0348 | 0.038 | 0.16 | 0.1060 | 0.043 | 0.068 |

- For static bed height 25cm and expansion ratio R=3 and 50:50 mixture

**Table 3.4.5 :** Min. and Max. semi-fluidization velocities at constant gas and liquid flow rates

| For constant gas flow rate | | | For constant liquid flow rate | | |
|---|---|---|---|---|---|
| $U_g$(m/s) | $U_{lmsf}$ (m/s) | $U_{lMsf}$ (m/s) | $U_l$(m/s) | $U_{gmsf}$(m/s) | $U_{gMsf}$(m/s) |
| 0.0106 | 0.048 | 0.200 | 0.0424 | 0.050 | 0.085 |
| 0.0148 | 0.044 | 0.170 | 0.0636 | 0.045 | 0.080 |
| 0.0212 | 0.041 | 0.165 | 0.0848 | 0.042 | 0.075 |
| 0.0348 | 0.039 | 0.150 | 0.1060 | 0.040 | 0.070 |

# CHAPTER 4

# DEVELOPMENT OF CORRELATIONS

### 4.1 HEIGHT OF PACKED BED FORMATION

The method of experimentation is based on factorial design analysis[3] and dimensional analysis in order to bring out the effect of variables on the response The scope of the factors consider for factorial experimentation are listed in table 4.1.1. The variables which affect the height of the top packed bed are initial static bed height, superficial gas velocity and superficial liquid velocity.

**Table 4.1** **(**Scope of the factors for hydrodynamics for factorial Design Analysis)

| Sl no. | variables | General symbol | Factorial design symbol | Minimum level(-1) | Maximum level(+1) | Magnitude of variables |
|---|---|---|---|---|---|---|
| 1 | Static bed height(cm) | $H_s$ | A | 10 | 25 | 10,15,20,25 |
| 2 | Gas flow rate(lpm) | $V_g$ | B | 20 | 30 | 20,25,30 |
| 3 | Liquid flow rate(lpm) | $V_l$ | C | 20 | 50 | 20,30,40,50 |

The model equations are assumed to be linear and the equations take the general form,

$$Y= (b_0+b_1A+b_2B+b_3C+\ldots+b_{12}AB+b_{13}AC+\ldots+b_{123}ABC) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.1)$$

I) Coefficients are calculated by the Yates technique:

$$b_i= \Sigma\ (\alpha_i Y_i)/N$$

II) Calculations of the level of variables:

A: Level for static bed height= (Static bed height – 17.5)/7.5

B: Level for gas flow rate = (gas flow rate - 25)/5

C: Level for liquid flow rate = (liquid flow rate – 35)/15

**Table: 4.2** (The effects of parameters as per factorial design analysis)

| Sl. No. | Treatment Combination | Experimental data | 1 | 2 | 3 | Effect (3)/4 | Sum of squares $(3)^2/8$ |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 0.520 | 0.532 | 1.396 | 3.646 | | |
| 2 | a | 0.012 | 0.864 | 2.250 | 2.450 | 0.6125 | 0.75000 |
| 3 | b | 0.680 | 0.980 | 1.004 | -0.622 | 0.1550 | 0.04800 |
| 4 | ab | 0.184 | 1.270 | 1.450 | 0.202 | 0.0505 | 0.00500 |
| 5 | c | 0.900 | 0.508 | -0.332 | -0.854 | -.2130 | 0.09100 |
| 6 | ac | 0.080 | 0.496 | -0.290 | -0.446 | 0.1150 | 0.02500 |
| 7 | bc | 0.950 | 0.820 | 0.012 | -0.042 | 0.0105 | 0.00020 |
| 8 | abc | 0.320 | 0.630 | 0.190 | -0.178 | -0.0440 | 0.00396 |

The following equation has been obtained:

$$Y= 0.456+ 0.306*A- 0.078*B+ 0.025*A*B- 0.1067*C- 0.0557*A*C- 0.0053*B*C- 0.0223*A*B*C \quad \text{--------------------------------------(4.2)}$$

The value of the coefficients indicates the magnitude of the effect of the variables and the sign of the coefficient gives the direction of the effect of the variable. That is a positive coefficient indicating an increasing in the value of the responses with increase in the value of the variable and a negative coefficient showing that the response decreases with increase in the value of the variable.

Equation developed by dimensional analysis:

$$\frac{Hpa}{Hs} = 0.888*\frac{Hs}{Dc}^{-0.46}*\frac{Ug}{Uogsf}^{0.067}*\frac{Ul}{Uolsf}^{0.124}*\frac{dp}{Dc}^{0.17}*R^{-0.505} \quad \text{------------(4.3)}$$

**Table: 4.3** :Comparison of experimental values of top packed bed formation with that of the calculated ones (equation 4.2 and 4.3)

| Static bed height (cm) | Gas flow rate(lpm) | Liquid flow rate(lpm) | $d_p$(cm) | R | $H_{pa}/H_s$ (exp) | $H_{pa}/H_s$ (cal) (eq 4.2) | $H_{pa}/H_s$ (cal) (eq 4.3) | % Dev. (eq 4.2) | % Dev. (eq 4.3) |
|---|---|---|---|---|---|---|---|---|---|
| 10 | 20 | 20 | 0.179 | 2 | 0.50 | 0.3210 | 0.325 | 24 | 23 |
| 15 | 20 | 20 | 0.185 | 2 | 0.52 | 0.5306 | 0.510 | 1.9 | 1.9 |
| 20 | 20 | 20 | 0.190 | 2 | 0.80 | 0.7402 | 0.770 | 8.0 | 3.0 |
| 25 | 20 | 20 | 0.195 | 2 | 0.90 | 0.9480 | 0.880 | 5.0 | 2.0 |
| 10 | 25 | 30 | 0.179 | 3 | 0.18 | 0.1670 | 0.170 | 7.0 | 5.0 |
| 15 | 25 | 30 | 0.185 | 3 | 0.32 | 0.3840 | 0.353 | 16 | 9.0 |
| 20 | 25 | 30 | 0.190 | 3 | 0.68 | 0.5990 | 0.650 | 13 | 4.0 |
| 25 | 25 | 30 | 0.195 | 3 | 0.88 | 0.8160 | 0.830 | 7.0 | 6.0 |
| 10 | 30 | 40 | 0.179 | 3.5 | 0.04 | 0.0350 | 0.048 | 14 | 16 |
| 15 | 30 | 40 | 0.185 | 3.5 | 0.32 | 0.2390 | 0.300 | 33 | 6.0 |
| 20 | 30 | 40 | 0.190 | 3.5 | 0.48 | 0.4420 | 0.420 | 8.0 | 14 |
| 25 | 30 | 40 | 0.195 | 3.5 | 0.68 | 0.6450 | 0.660 | 5.0 | 3.0 |
| 10 | 30 | 50 | 0.179 | 4 | 0.0121 | 0.0130 | 0.0123 | 6.9 | 1.6 |
| 15 | 30 | 50 | 0.185 | 4 | 0.18 | 0.1810 | 0.177 | 0.5 | 1.7 |
| 20 | 30 | 50 | 0.190 | 4 | 0.32 | 0.3500 | 0.330 | 8.0 | 3.0 |
| 25 | 30 | 50 | 0.195 | 4 | 0.56 | 0.5190 | 0.530 | 7.0 | 5.0 |

## 4.2 <u>MINIMUM LIQUID SEMI FLUIDIZATION VELOCITY</u>

**Table 4.4** **(**Scope of the factors for hydrodynamics for factorial Design Analysis)

| Sl no. | variables | General symbol | Factorial design symbol | Minimum level(-1) | Maximum level(+1) | Magnitude of variables |
|---|---|---|---|---|---|---|
| 1 | Particle diameter(cm) | $d_p$ | A | 0.179 | 0.195 | 0.179,0.185,0.19,0.195 |
| 2 | Expansion ratio | R | B | 2 | 4 | 2,3,3.5,4 |
| 3 | Gas flow rate(lpm) | $V_g$ | C | 5 | 15 | 5,7,10,15 |

The model equations are assumed to be linear and the equations take the general form:

$$Y= (b_0+b_1A+b_2B+b_3C+\ldots+b_{12}AB+b_{13}AC+\ldots+b_{123}ABC)$$

I) Coefficients are calculated by the Yates technique: $b_i= \Sigma (\alpha_i Y_i)/N)$

II) Calculations of the level of variables: $A = (d_p – 0.187)/0.008$;

$B = (R – 3.125)/1.125$; $C = (U_g – 9.25)/4.25$

**Table 4.5** (The effects of parameters as per factorial design analysis)

| Sl. No. | Treatment Combination | Experimental data | 1 | 2 | 3 | Effect (3)/4 | Sum of squares $(3)^2/8$ |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 4.0 | 8.4 | 18.9 | 32 | | |
| 2 | a | 4.4 | 10.5 | 13.1 | -1.6 | -0.4 | 0.320 |
| 3 | b | 5.0 | 5.4 | -0.9 | -4.4 | -1.1 | 2.420 |
| 4 | ab | 5.5 | 7.7 | -0.7 | 0 | 0 | 0 |
| 5 | c | 2.5 | -0.4 | -2.1 | 5.8 | 1.45 | 4.200 |
| 6 | ac | 2.9 | -0.5 | -2.3 | -0.2 | -0.05 | 0.005 |
| 7 | bc | 3.7 | -0.4 | 0.1 | 0.2 | 0.05 | 0.005 |
| 8 | abc | 4.0 | -0.3 | -0.1 | 0.2 | 0.05 | 0.005 |

The following equation has been obtained:

Y=4-0.2*A-0.55B+0.725C-0.025AC+0.025BC+0.025ABC--------------------------(4.4)

### 4.3 MAXIMUM SEMI FLUIDIZATION VELOCITY

**Table 4.6** (The effects of parameters as per factorial design analysis)

| Sl. No. | Treatment Combination | Experimental data | 1 | 2 | 3 | Effect (3)/4 | Sum of squares $(3)^2/8$ |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 17 | 35 | 74 | 134 | | |
| 2 | a | 18 | 39 | 60 | -4 | -1.0 | 2.0 |
| 3 | b | 19 | 29 | -2 | -6 | -1.5 | 4.5 |
| 4 | ab | 20 | 31 | -2 | 0 | 0 | 0 |
| 5 | c | 14 | -1 | -4 | 14 | 3.5 | 24.5 |
| 6 | ac | 15 | -1 | -2 | 0 | 0 | 0 |
| 7 | bc | 15 | -1 | 0 | -2 | -0.05 | 1 |
| 8 | abc | 16 | -1 | 0 | 0 | 0 | 0 |

The following equation has been developed:

$$Y=16.75-0.5A-0.75B+1.75C-0.25BC \quad \text{-------------------------------------------------(4.4)}$$

**Table 4.7** (Comparison of experimental values with calculated values)

| $d_p$(cm) | R | $V_g$(lpm) | $U_{lmsf}$ (exp) | $U_{lmsf}$ (cal) | %dev | $U_{lMsf}$ (exp) | $U_{lMsf}$ (cal) | %dev |
|---|---|---|---|---|---|---|---|---|
| 0.179 | 2 | 5 | 4.0 | 4.00 | 0 | 17.0. | 16.00 | 6.0 |
| 0.185 | 2 | 5 | 3.6 | 3.80 | 5.20 | 16.0 | 15.62 | 2.4 |
| 0.190 | 2 | 5 | 3.7 | 3.79 | 2.30 | 15.5 | 15.31 | 1.2 |
| 0.195 | 2 | 5 | 3.9 | 3.70 | 5.40 | 15.6 | 15.00 | 4.0 |
| 0.179 | 3 | 7 | 4.4 | 3.86 | 13.0 | 16.5 | 16.39 | 0.67 |
| 0.185 | 3 | 7 | 3.8 | 3.72 | 2.00 | 16.2 | 16.00 | 1.25 |
| 0.190 | 3 | 7 | 3.7 | 3.61 | 2.40 | 16.0 | 15.70 | 1.9 |
| 0.195 | 3 | 7 | 3.6 | 3.49 | 3.15 | 15.5 | 15.39 | 0.7 |
| 0.179 | 3.5 | 10 | 4.3 | 4.14 | 3.80 | 17.0 | 17.29 | 1.6 |
| 0.185 | 3.5 | 10 | 4.2 | 3.99 | 5.20 | 17.2 | 16.90 | 1.7 |
| 0.190 | 3.5 | 10 | 3.9 | 3.86 | 1.03 | 17.0 | 16.60 | 2.4 |
| 0.195 | 3.5 | 10 | 3.8 | 3.74 | 1.60 | 16.6 | 16.29 | 1.9 |
| 0.179 | 4 | 15 | 5.0 | 4.78 | 4.60 | 18.0 | 18.77 | 4.1 |
| 0.185 | 4 | 15 | 4.7 | 4.63 | 1.50 | 18.2 | 18.39 | 1.03 |
| 0.190 | 4 | 15 | 4.6 | 4.50 | 2.20 | 18.1 | 18.08 | 0.11 |
| 0.195 | 4 | 15 | 5.5 | 5.20 | 7.00 | 17.5 | 17.77 | 1.5 |

**Table 4.8** Comparing min. liquid semi fluidization velocity for binary mixtures with that for pure component irregular particles

$U_{lmsf} = 0.3832 * dp^{0.4373} * R^{0.3982} * Ug^{-0.2354}$ [4]

| dp(cm) | R | $V_g$(lpm) | $U_{lmsf}$ (binary mix) | $U_{lmsf}$(pure component) |
|---|---|---|---|---|
| 0.179 | 2 | 5 | 4.0 | 9.20 |
| 0.185 | 2 | 5 | 3.6 | 9.30 |
| 0.190 | 2 | 5 | 3.7 | 9.50 |
| 0.195 | 2 | 5 | 3.9 | 9.60 |
| 0.179 | 3 | 7 | 4.4 | 10.0 |
| 0.185 | 3 | 7 | 3.8 | 10.2 |
| 0.190 | 3 | 7 | 3.7 | 10.3 |
| 0.195 | 3 | 7 | 3.6 | 10.4 |
| 0.179 | 3.5 | 10 | 4.3 | 9.83 |
| 0.185 | 3.5 | 10 | 4.2 | 9.97 |
| 0.190 | 3.5 | 10 | 3.9 | 10.09 |
| 0.195 | 3.5 | 10 | 3.8 | 10.2 |
| 0.179 | 4 | 15 | 5.0 | 9.42 |
| 0.185 | 4 | 15 | 4.7 | 9.56 |
| 0.190 | 4 | 15 | 4.6 | 9.67 |
| 0.195 | 4 | 15 | 5.5 | 9.78 |

# CHAPTER 5

# CONCLUSIONS

Three phase semi fluidization has potential application in chemical and bio –chemical reactors and in waste water treatment reactor. For designing such systems, hydrodynamic parameters should be known. In that direction present work will be useful. The important hydrodynamic parameters like minimum and maximum semi fluidization velocity and packed bed formation have been quantified by developing different correlations with the help of experimental data. The values calculated from these correlations also compare fairly well with the experimental values. Further it has been observed that use of the correlations developed earlier for single component systems for the prediction of such hydrodynamic parameters is not feasible due to high values of deviation. Therefore, the developed correlation can be used while dealing with binary irregular mixtures. The present correlations can be used with fair accuracy for the design of three phase semi fluidized beds systems handling irregular binaries within the range of the variables studied.

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